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6. AUTHOR(S)

Balladin, Ulf I, Werchan, Paul, Eddy, Travis

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Armstrong Laboratory (AFMC)
Crew Systems Directorate
Crew Technology Division
2405 D Dr Ste 1
Brooks AFB TX 78235-5104

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TCD systems have been successfully used in clinical practice for estimating cerebral perfusion by registering blood flow velocity in the middle cerebral artery. However, when used in centrifuges, probe movement during high +G_i have resulted in the loss of Doppler signal making interpretations of data very difficult. To solve this problem, the Doppler probe and three electrical motors were mounted on a tightly fitted helmet. Remote control of these motors allows precise tilting and sliding of the probe during G exposures. Vertical movement of the probe is recorded when a good flow velocity signal is achieved. On succeeding G-exposures the probe is moved to the predicted positions for different G-loads when the G-load changes. A computer program to automate this process is currently under development. With this device, blood flow velocity in the middle cerebral artery can be registered at G-loads up to 9 +G_i with increased accuracy.

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REMOTE CONTROL OF TRANSCRANIAL DOPPLER (TCD) PROBE DURING CENTRIFUGE EXPOSURES UP TO $9 + G_z$

ULF I BALLDIN, Ph.D., M.D.
Research Director, Visiting Scientist

Paul Werchan, Ph.D.
Research Physiologist

94-03098



Travis Eddy
Mechanical Engineering cooperative student

National Defence Research Establishment, Sweden
and Armstrong Laboratory, Brooks AFB, Texas, USA

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ABSTRACT

TCD systems have been successfully used in clinical practice for estimating cerebral perfusion by registering blood flow velocity in the middle cerebral artery. However, when used in centrifuges, probe movement during high $+G_z$ have resulted in the loss of Doppler signal making interpretations of data very difficult.

To solve this problem, the Doppler probe and three electrical motors were mounted on a tightly fitted helmet. Remote control of these motors allows precise tilting and sliding of the probe during G exposures. Vertical movement of the probe is recorded when a good flow velocity signal is achieved. On succeeding G-exposures the probe is moved to the predicted positions for different G-loads when the G-load changes. A computer program to automate this process is currently under development. With this device, blood flow velocity in the middle cerebral artery can be registered at G-loads up to $9 + G_z$ with increased accuracy.

INTRODUCTION

G-induced loss of consciousness (G-LOC) has been the cause of several fatal accidents, especially with high performance (i.e. $9 G$) fighter aircraft. Many more incidents at higher altitudes have also occurred without any accidents. Due to the amnesia associated with G-LOC some pilots may not even know that they have had a G-LOC. Additionally, some pilots may be afraid of reporting G-LOC incidences due to the potential for a negative impact on their flying career. Different methods and tools to detect and study impending G-LOC have been tried for many years.

Transcranial Doppler Systems (TCD) use a 2 MHz ultrasound pulsed beam to penetrate the temporal region of the skull to a depth of 10 cm (1). The shift in frequency of the emitted ultrasound is directly proportional to the velocity of the blood flow in the vessels in the path of insonation. It has successfully been used in clinical practice for estimating cerebral blood perfusion and for identification of aneurysm and vasospasm in the middle cerebral artery (MCA); indicating different vascular brain diseases. It has also

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been used to detect blood flow velocity in other cerebral blood vessels, such as anterior cerebral, internal carotid, posterior cerebral, ophthalmic, vertebral and basilar arteries.

In 1988, the Armstrong Laboratory acquired and began using the first TCD device which was specially designed for the human centrifuge (3). Anticipating problems with movements, the ultrasound probe and positioning hardware were mounted on a rigid headband assembly. In the earliest experiments, the TCD was successful in monitoring brain blood flow during centrifuge exposures up to 6 +Gz (6). A total loss of blood flow velocity was found during an unintentional G-LOC episode. However, this loss of blood flow may have been a false conclusion, if the probe moved significantly during the G exposure and the loss of Doppler signal occurred. An additional problem was identified pertaining to the uncomfortable fit of the headband which was maximally tightened during the G exposure to prevent slippage.

When the TCD system was used in the centrifuge at higher G-levels and when the subject performed the straining maneuvers, probe movements during high +G, often resulted in the loss of Doppler signal making interpretations of this data very difficult.

To solve the problems with movement and comfort, the Doppler probe was redesigned using a helmet for greater stability and to provide a platform for the attachment of 3 miniature electrical motors (Fig. 1 a-c) for remote focus of the ultrasound probe. This remote control system allows precise tilting and sliding of the probe during G exposures.

METHODS

Prior to using this Transcranial

Doppler device, a good TCD signal from the middle cerebral artery (MCA) must be obtained with a hand held probe. Thereafter, the subject dons the helmet and fastens a chin strap. The MCA signal is relocated by coarse vertical and horizontal adjustments of the probe using a slide mechanism with a set screw (d). Initial tilting of the probe may also be accomplished with a knob located on top of the device (e) and the tension of the probe against the head can be adjusted (f). Once coarse adjustments are made, the motors are utilized to "fine tune" the Doppler signal by using a dual joy-stick control box. Using the two motors linked to the probe body an adjustment of probe tilt can be made. Using the motor attached to the slide mechanism the entire probe assembly can be raised or lowered as needed. Typically, the motor positions are preset such that maximal range of motion is available during centrifuge exposures.

Located in the centrifuge control room is a data acquisition system consisting of a PC 386, a Macintosh FX, two VCR recorders and a quad-video mixer. The PC runs the software necessary for real-time FFT frequency analysis of the doppler output audio. The Macintosh is responsible for providing real-time tracking of motor and thus probe position if adjustments are made during the centrifuge exposures. Vertical probe movements are indicated by a sliding bar graph and the probe tilt is recorded using an X-Y coordinate graph on the quad-video mixer screen. Both frontal and side views of the subject are recorded as part of the quad mix to verify the probe movement.

RESULTS

During a typical experiment, a good signal was obtained at rest (1 G). During a gradual onset (0.1 G/s) G-exposure, the probe was moved upwards by the joy-stick, as necessary to

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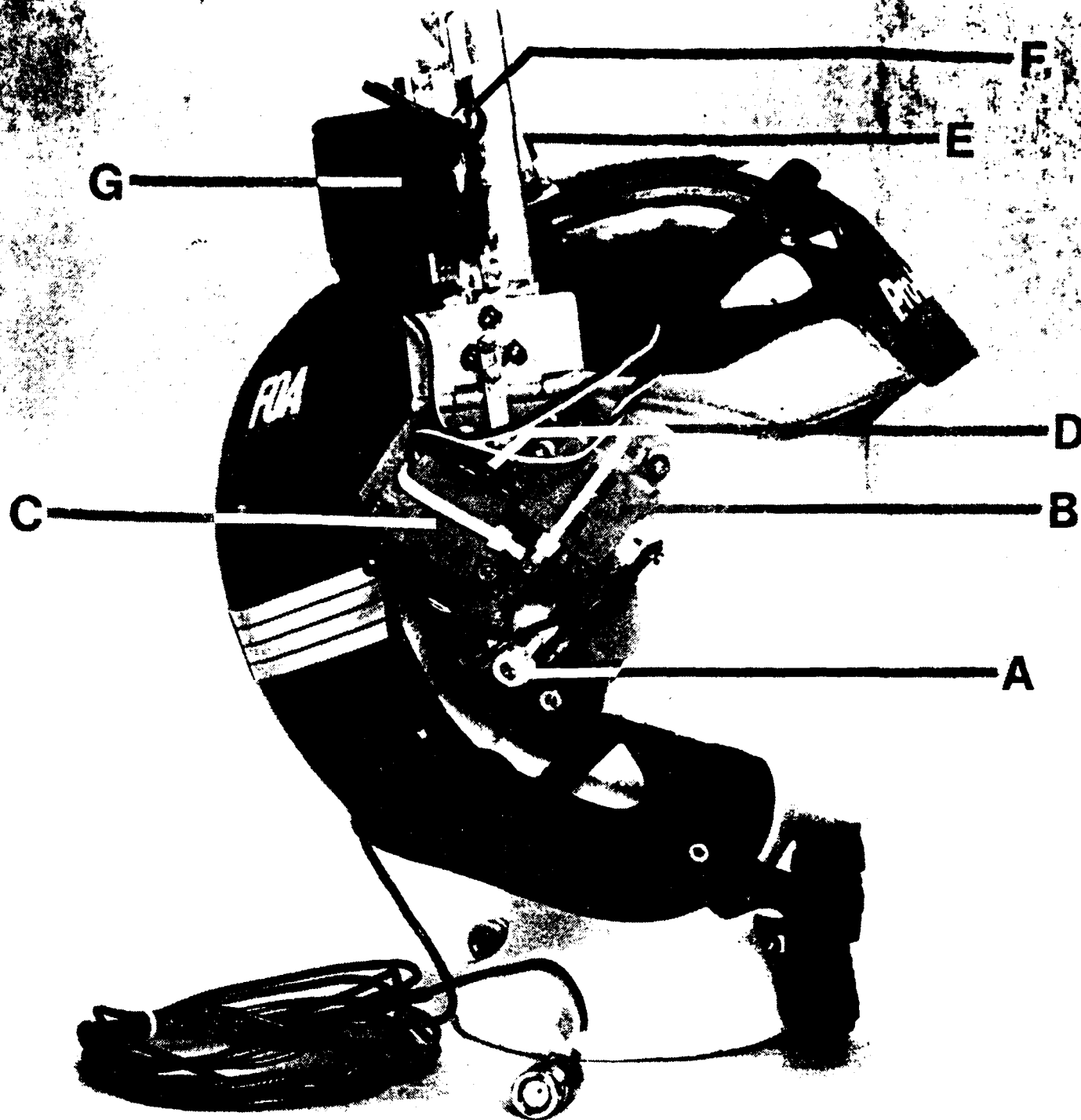


Fig. 1. The helmet with remote controlled probe. A) TCD-probe, B) and C) motors for tilting, D) knob to apply pressure of the probe to the skull, E) knob for gross tilting, F) knob for gross vertical movements, and G) motor for vertical movements of the probe.

maintain a proper signal. Typically the probe had to be raised by about 4 to 8 mm when G-load was increased from 1 to 9 +Gz. When the probe was repositioned to the original (1 G) position during the G-exposure, the signal usually disappeared or became very weak but would return again when the probe was moved back to its previous position. Upon returning to 1 G with the probe in the upward position, the signal typically vanished and was regained when the probe was returned to its original position. Similar phenomena were seen during rapid onset runs (6 G/s) up to 9 +Gz.

During a simulated air combat maneuvers (SACM), G-profiles consisting of 10 s periods at alternating 5 and 9 G, with rapid onset, the signal usually disappeared during the 5 or 9 G peak, if the probe was not moved. If the probe was moved upwards during subsequent high G peaks to the position needed for a proper signal at the different G-loads, as decided in earlier runs, the signal usually returned. If the signal did not return with the predecide movement, it was an indication of a physiological cessation of the blood flow in the middle cerebral artery with the possibility of an impending G-LOC.

Initially, a calibration of the necessary vertical movements of the probe for maintaining a good cerebral blood flow velocity must be established and recorded at different G-loads in the centrifuge for each subject. During subsequent G-exposures to these same G-levels, the probe must be moved to the predicted positions for the various G-load,s to regain a good flow velocity signal.

DISCUSSION

The body's cardiovascular response to rapid acceleration stress is undoubtedly the most complex seen in the

history of physiological research. Acceleration physiologists have attempted to describe man's response to high G by using a variety of tools and techniques, which can be broadly classified as either invasive or non-invasive. Based on safety considerations the trend in recent years has been to develop or utilize objective measurement tools which are exclusively non-invasive. Every attempt to achieve this goal has met with difficulties due to the movement of either the equipment or the body itself during high-G exposures. The undesirable results of movement range from superimposed motion artifacts, to suspect data and/or the complete loss of data collection.

As a subcategory of cardiovascular research, the measurement of brain blood flow during centrifugation is probably the most difficult of any organ in the body to accomplish. Reasons for this include: (a) the extreme dynamic fluctuation of CBF during G (b) the complex vascular anatomy of the brain (c) the complication of extracerebral contamination, and (d) the protective and impenetrable containment of the brain by the skull.

Non-invasive extracranial blood flow measurements during increased G-loads have been used in the past with varying success. The blood flow in the superficial temporal artery has been measured with the ultrasound Doppler technique (5). This technique may successfully be used at low G-levels, but when reaching G-levels above 7 G, and when the subjects execute their muscular and respiratory straining maneuvers to maintain a sufficient cerebral blood pressure, it is very difficult to maintain a proper Doppler signal. The relative movements between the probe attached to the skin and the skull forces the focus of the ultrasound waves outside the blood vessel, whereupon the signal is lost.

Similar phenomena are encountered when using infrared laser Doppler skin capillary flow measurements in the head regions (Ballidin, unpublished results). Rapid, irregular changes in the skin capillary flow, and changes due to shifts in skin temperature make this method highly uncertain.

When using the ear opacity or ear oximetry technique, one will have a good indication when the blood flow ceases in the external ear, even during high G-levels (2, 7). The cessation of blood flow in the ear usually precedes G-induced loss of consciousness. It may not, however, be a good indicator of the blood flow changes within the brain itself. The oxygen saturation of blood is usually reduced slowly in long duration centrifuge runs at higher G-levels but may be of less importance in rapid onset G-loads. All these techniques, however, rely upon measurements of blood circulation outside the brain and the cranium. It is known that the autoregulation of cerebral blood flow and extracerebral blood flow is very different.

There are some invasive methods to investigate the brain blood flow, such as radiological methods (cerebral angiography) and the use of radioactive Xe^{133} scintigraphy for studying regional blood flow changes. However, they rely upon heavy equipment, sterile intravascular injections and a steady state for an extended time period (i.e., minutes). They are, therefore, not useful in very rapidly changing environments, such as simulated aerial combat maneuvers with 10 to 15 s periods of varying between G-loads.

Indirect measurements of the oxidative status of the brain with Oxidative Metabolism Near Infrared Monitor has been used during acceleration(4). This apparatus measures the relative quantities of brain hemoglobin,

oxygenated hemoglobin, blood volume and oxidative status of cytochrome oxidase. However, during centrifugation at higher and rapidly shifting G-loads, this method appears not very practical, again due to technical difficulties and artifacts attributed to movements of the probe.

The non-invasive TCD gives a good registration of blood flow velocity and, thus, blood supply to major regions of the brain. Registration of the blood flow velocity in MCA is advantageous because of the very small angle between the Doppler ultrasound beam and the main stream of the blood vessel. A typical window for the TCD signal of the middle cerebral artery is about 4 mm, which is about the same size as the MCA. The ultrasound beam must, therefore, be restricted to operate within this limit. When the Doppler signal is out of focus due to large probe movements, the signal will be lost. With remote control of the probe, compensation may be made for the relative movements between the probe and the skull thus decreasing the risk of losing the TCD signal. Thus the possibility of a false conclusion of brain blood flow cessation during high G-loads may be avoided. This will make the device more suitable for use during centrifuge exposures to high G-levels and during rapid shifts between G-loads. With this device blood flow velocity in the middle cerebral artery can be registered at G-loads up to 9 +G, with increased certainty and accuracy.

The TCD device can provide important information regarding cerebral hemodynamics during +Gz exposures and will provide a more objective index of human +Gz stress, +Gz protection measures and impending G-LOC in the centrifuge.

A computer program to automate this

process is currently under development. When the appropriate movement of the probe for different G-levels have been established and coordinates registered, the computer will automatically provide input to the motor to reposition the probe at the different G-levels.

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Biography

Ulf Balldin, Research Director, National Defence Research Establishment, Sweden, and ordinarily Chief, Institute of Aviation Medicine. B.A., M.D. and Ph.D., University of Lund, Sweden. Naval Diving Medical Officer and Air Force Flight Surgeon. Fellow in Aerospace Medicine, Council Member and past Vice President of Aerospace Medical Association. Director, International Academy of Aviation and Space Medicine. US Commercial Pilot license (instrument) with more than 1200 hours. As adj professor in Aerospace Medicine responsible for the acceleration research program at the centrifuge, Karolinska Institute, where he tested extended coverage anti-G suits with PBG. Currently working with acceleration research at the Armstrong Laboratory, Brooks AFB, Texas.

Dr Paul M. Werchan received a PhD in physiology from Louisiana State University Medical Center in 1986. Currently, he is a research physiologist in the Crew Technology Division, Crew Systems Directorate, Armstrong Laboratory, Brooks AFB. He manages a basic research team that focuses on the problem of consciousness (G-LOC). The approach is multidisciplinary and involves development of special research tools used on the AL human and small animal centrifuges to measure cerebral blood flow and metabolism in the high G environment before, during, or following G-LOC.

Travis Eddy is a Mechanical Engineering student at the University of Texas at Austin, Department of Mechanical Engineering.